Searching for the Proton's Spin:

Probing Δg with Polarized p+p Collisions via π Production

Astrid Morreale

08/22/08

Spin was first discovered in the context of the emission spectrum of alkali metals - "two-valued quantum degree of freedom" associated with the electron in the outermost shell.

In trying to understand splitting patterns and separations of line spectra, the concept of spin appeared.

"*it is indeed very clever but of course has nothing to do with reality*". *W. Pauli*

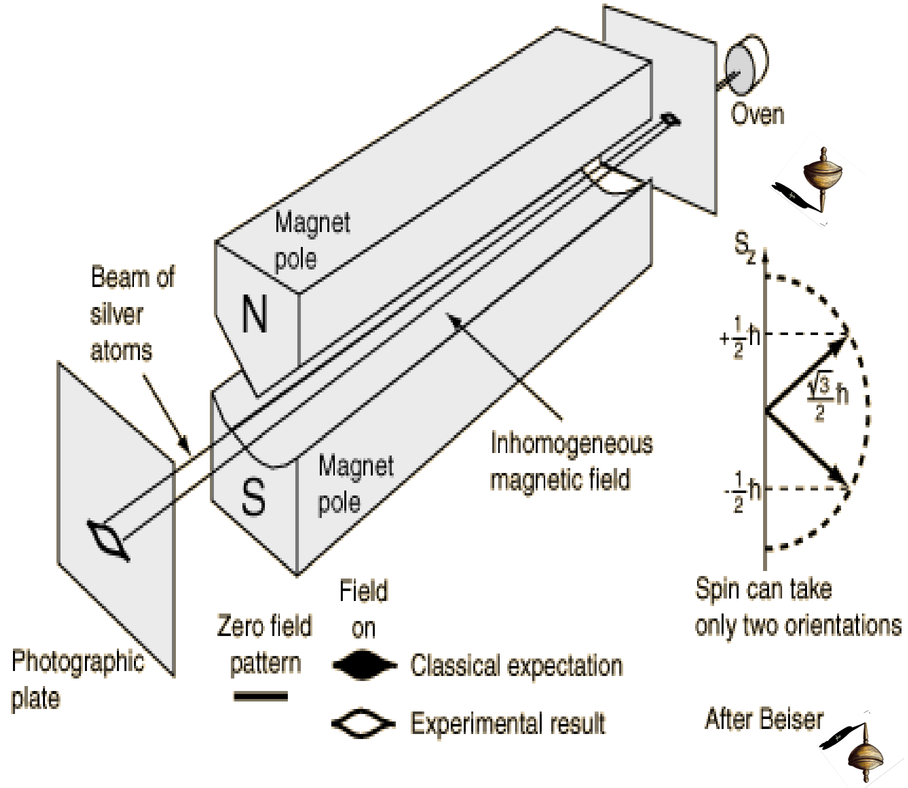
Splittings: The Stern-Gerlach Way
Intrinsic angular momentum

Protons, Neutrons, Electrons spin ½ (2 Possible Values)

Delta Barions (Δ++, Δ+, Δ0, Δ−) are spin +3/2 particles (four possible values for spin angular momentum.)

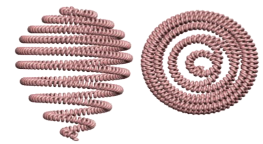
2S+1 Values

Vector Mesons, Photons, W, Z Bosons and Gluons, spin +1 (three possible values for spin angular momentum.)



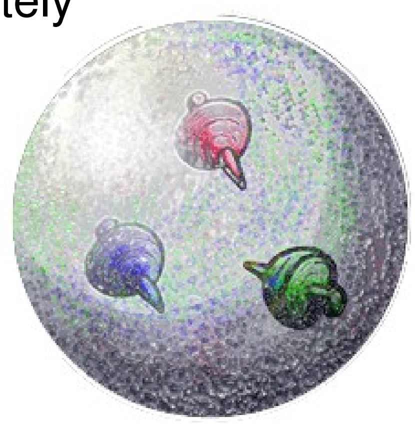
Intrinsic Spin Violates our intuition:

How can an elementary particle such as the e^- be point like and have perpetual angular momentum.?

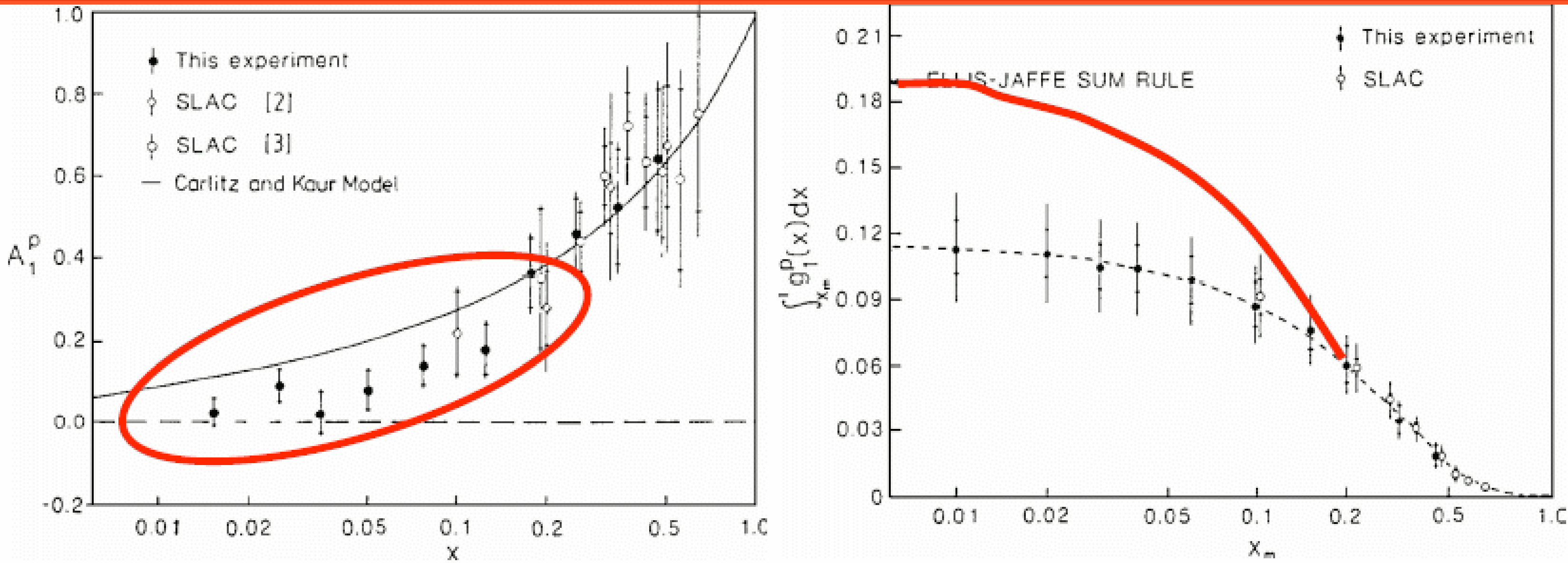


The Proton also has violated our intuition.
The Proton is composed of quarks, gluons and anti quarks.

We should expect the proton's spin to be predominately carried by its 3 valence quarks



Proton *Spin Crisis*



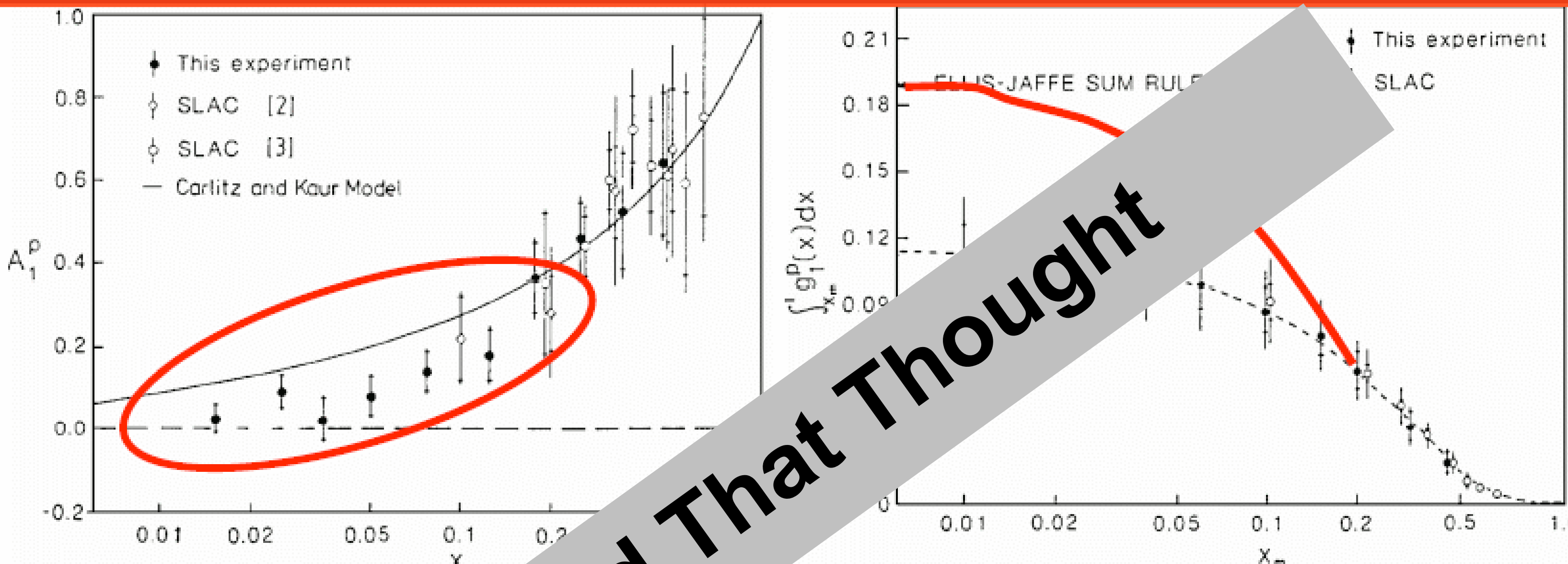
Quarks Don't Carry the Proton the Spin "1/2"

$\Delta\Sigma$ = (0.12) +/- (0.17) (EMC, 1989)

$\Delta\Sigma$ = 0.23 +/- 0.04 (SMC, 1998)

$\Delta\Sigma$ = 0.25 +/- 0.04 (SLAC, 1998)

Proton *Spin Crisis*



Hold That Thought

Quar... carry the Proton the Spin "1/2"

...) +/- (0.17) (EMC, 1989)

Δ... .23 +/- 0.04 (SMC, 1998)

$\Delta\Sigma$ = 0.25 +/- 0.04 (SLAC, 1998)

Outline of SPIN Structure

-The Proton has 2 spin-dependent Structure Functions: $g_1^p(x, Q^2)$ and $g_2^p(x, Q^2)$

x is the momentum fraction of the proton carried by the quark and Q^2 is the momentum transfer. (resolution of our probe)

- Define the asymmetry: $A^p(x, Q^2) = g_1^p(x, Q^2) / F_1^p(x, Q^2)$

- The First Moment of $g_1^p(x, Q^2)$ -> Γ_1^p.

$$\Gamma_1^p = \int_0^1 dx g_1^p(x, Q^2) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(Q^2)\left(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2)\right)$$

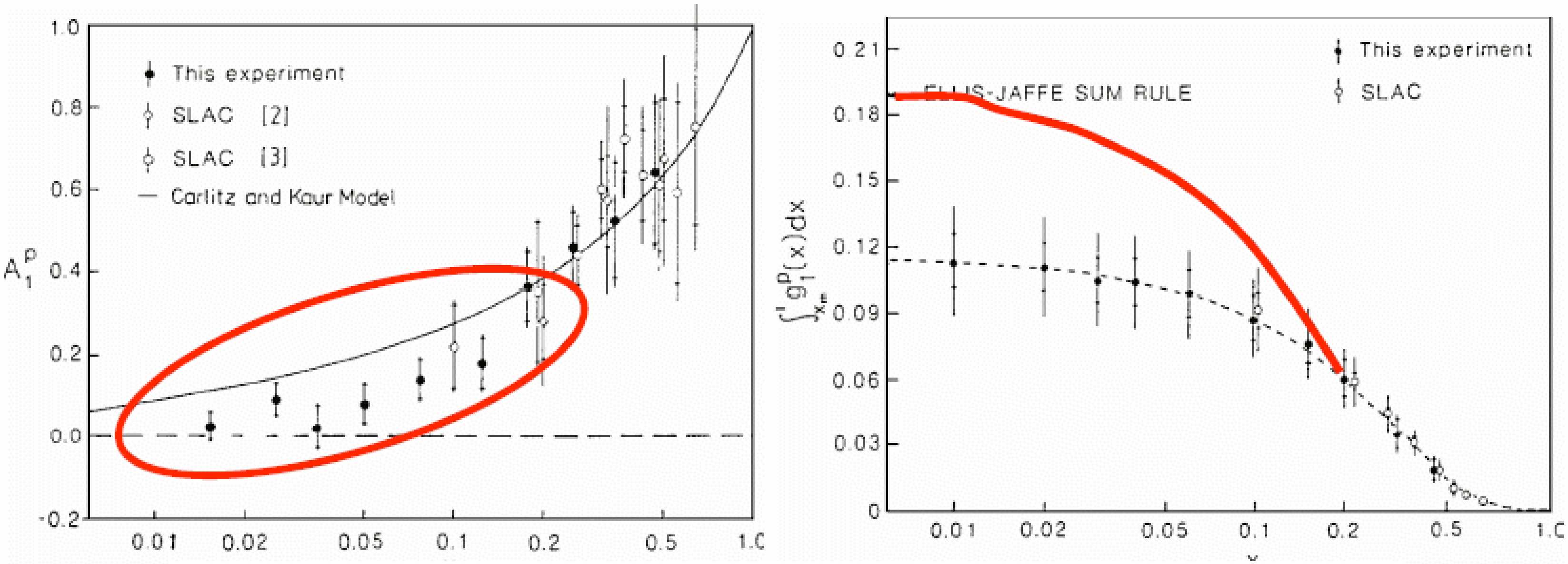
where $\Delta q_i(Q^2)$ is the probability of finding a quark or an anti quark of flavor i , and $\alpha_s \sim 1/\ln(Q^2/\Lambda^2)$

and $\Delta\Sigma = \Sigma_i \Delta q_i$

These two parameters Γ_1^p and $\Delta\Sigma$ can then be used to compare theory to data, working out though the quark probabilities and spin favored by the quark parton model, they came up with the following predictions: $\Delta u = \frac{4}{3}$, $\Delta d = -\frac{1}{3}$ and $\Delta s = 0$.

Which lead to a Γ_1^p = 0.28 and $\Delta\Sigma$ = 1 ($A^p(x, Q^2)$)

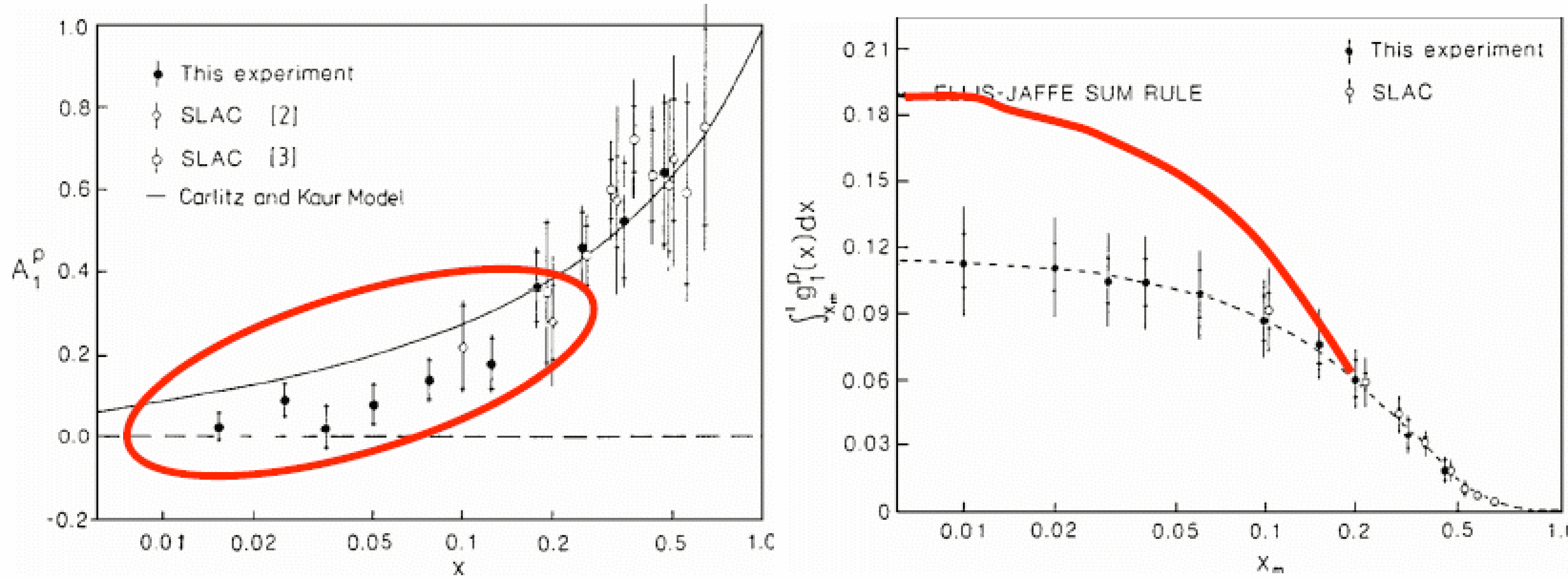
Proton Spin Crisis (1989)



$$\Delta u = 0.782 \pm 0.032 \pm 0.046$$
$$\Delta d = -0.471 \pm 0.032 \pm 0.046$$
$$\Delta s = -0.190 \pm 0.032 \pm 0.046$$

Nature's message: Take another look...ELSEWHERE!

Proton Spin Crisis (1989)



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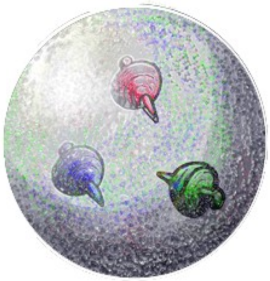
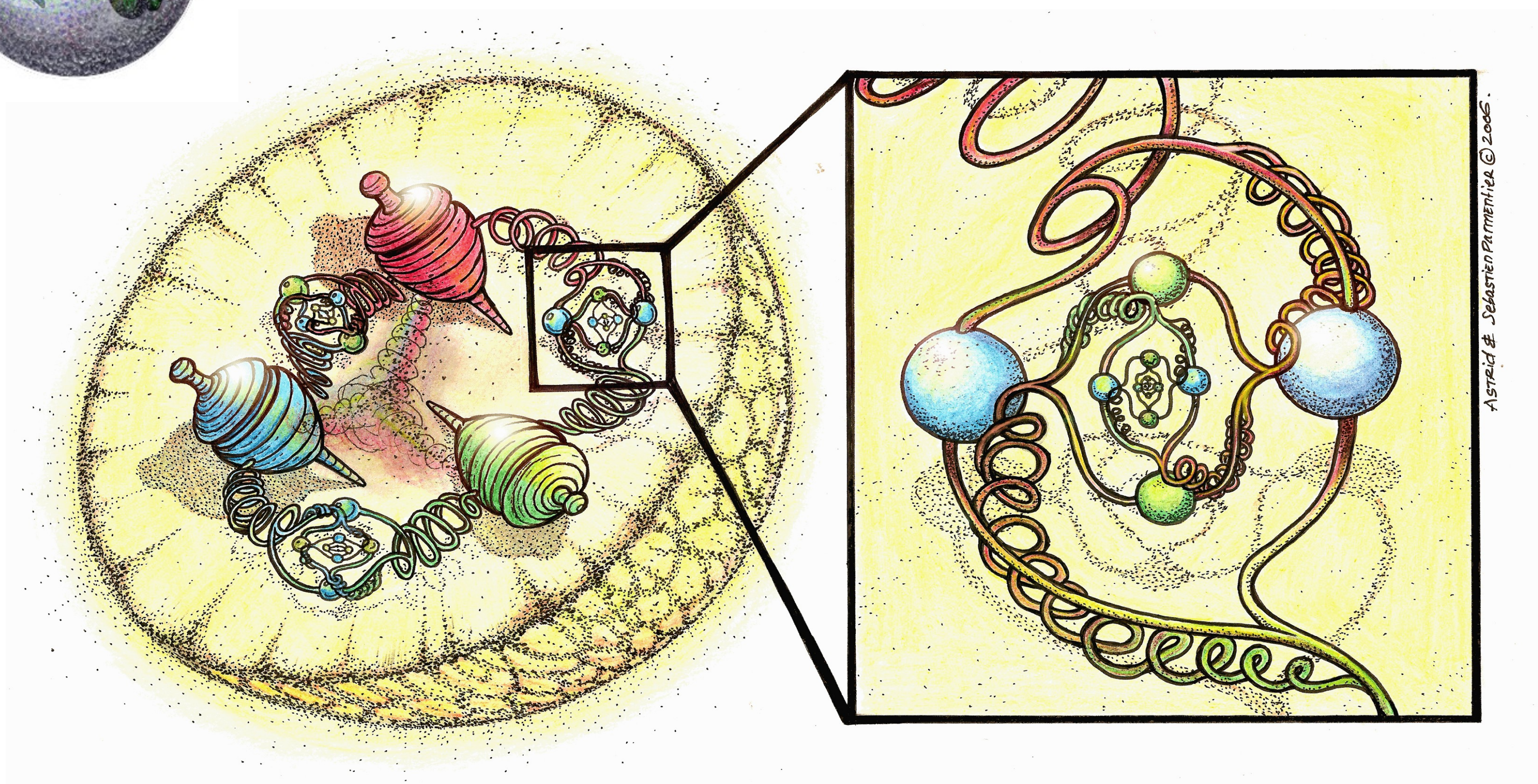
What was Wrong with the naïve QPM?

- The Proton does not only carry quarks within itself:

there are gluons and further, quarks and gluons may be moving around in orbits adding to the TOTAL SPIN.

The QCD Proton Picture





Longitudinal Spin Rule

~0.2 from DIS
"spin crisis"

RHIC Spin & SIDIS

GPD

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- ΔG: the spin of the gluons

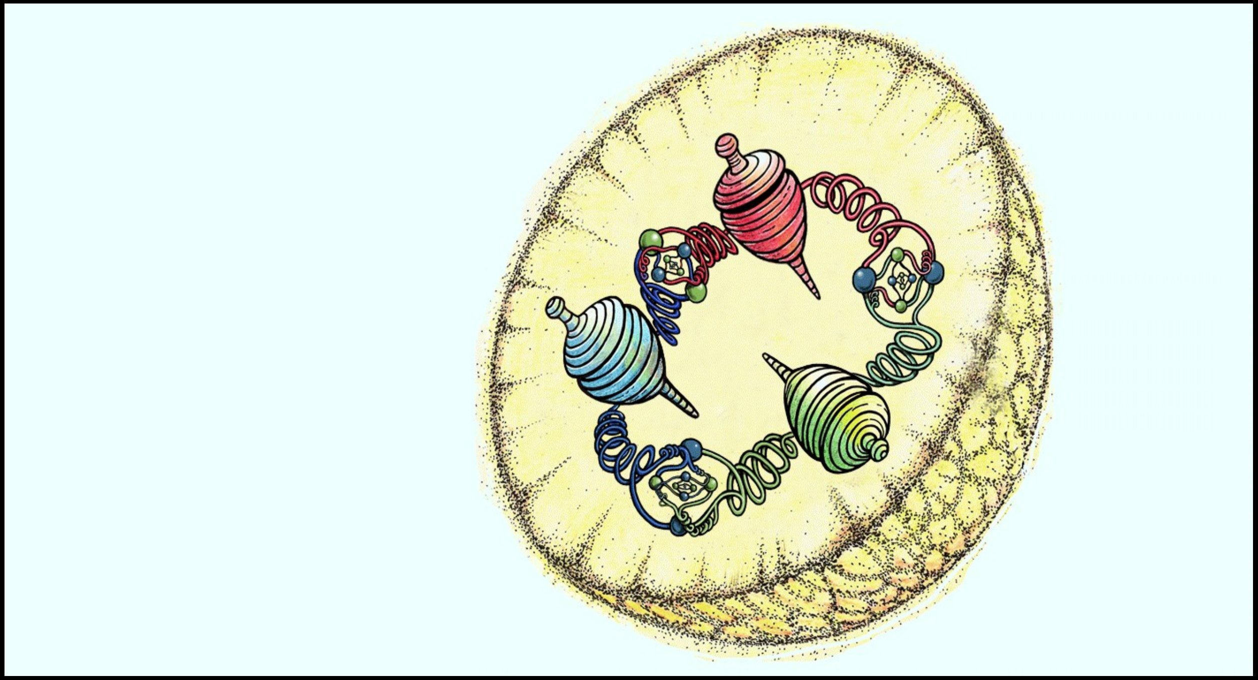
-L_z^q , L_z^g :orbital angular momenta

of the quarks and gluons

Transverse Spin Rule?

Bakker, Leader, Trueman
Phys.Rev.D70:114001,2004

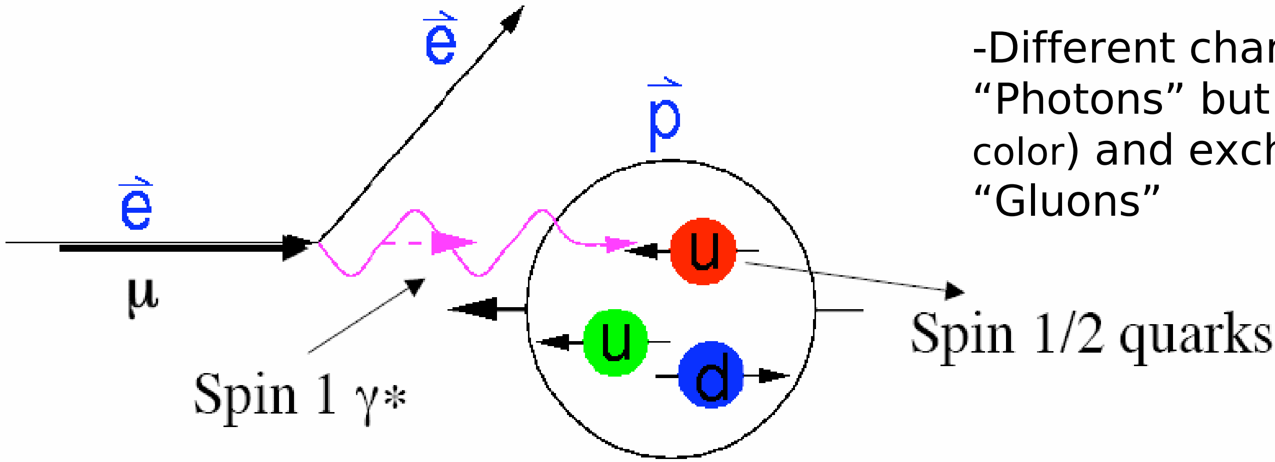
What Makes RHIC Unique: DIS vs pp



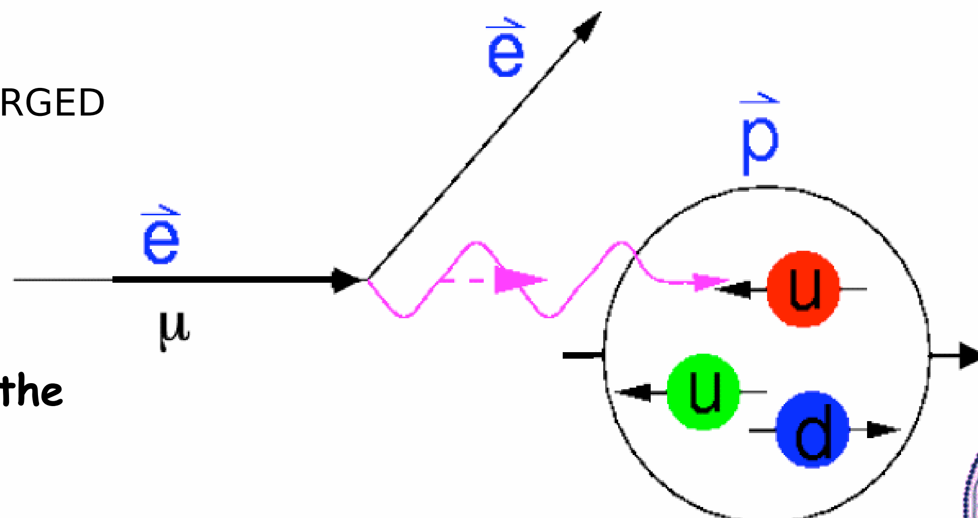
Fixed target experiments have given us a lot of insight, however we still do not have a complete understanding

-Quarks have electric and "color charge" (R,B,G)

-Different charges exchange "Photons" but Quarks (have color) and exchange in addition "Gluons"



– Photons can only interact with CHARGED particles (quarks)
– Since gluons are UNCHARGED, photons do not see gluons



We need polarized gluon-quark or gluon-gluon interactions to study the gluon polarization ΔG directly.

Polarized proton proton Collisions

- RHIC provides abundant source of polarized protons and can collide them at high energies.

-Each proton is an ample source of “glue”, can be used to probe the gluon’s role directly

-RHIC's High Energies keep the interpretation of results clean using pQCD

-We have appropriate detectors to look at such collisions

USEFUL TERMINOLOGY USED

Inclusive measurement:

A partial measurement. Only a few produced particles, sometimes only one, are singled out for identification and measurement, ignoring the details of all other interaction products.

Semi-inclusive:

Measurements that detect final state hadrons in coincidence with the scattered probe

Pseudorapidity

Spatial coordinate describing the angle of a particle relative to the beam axis it is defined as $\eta = -\ln(\tan(\theta/2))$ where theta is the angle relative to the beam axis. η does not depend on the energy of the particle, only on the polar angle of its trajectory

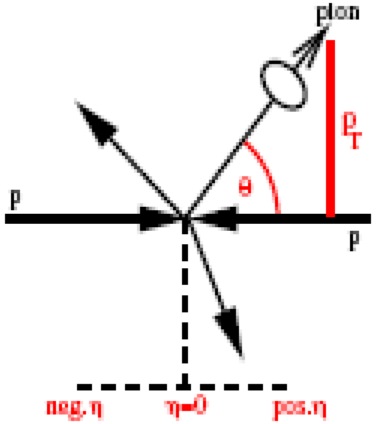
Factorization theorem:

High-energy QCD processes involve both perturbative and non-perturbative dynamics. The two dramatically different dynamics (characterized by Q and by a hadronic scale ,respectively) factorize.

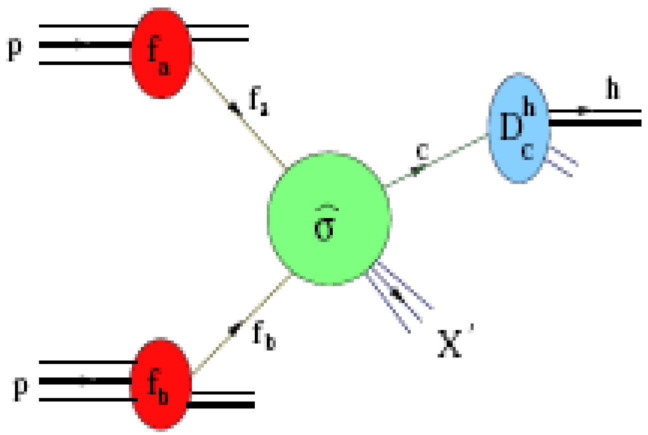
Universality of pdf's:They are the same regardless of the process involved.

FACTORIZATION

It is assumed that a differential cross section section can be written as the convolution of a parton density and a hard scattering process



factorization → theorem

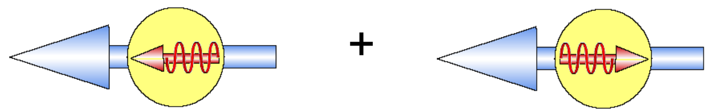


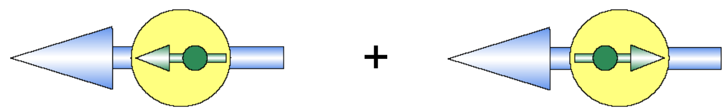
$$d\sigma = f_a \times f_b \times d\hat{\sigma} \times D_c^h$$

$$\frac{d\Delta\sigma^{\vec{p}\vec{p}\to\pi X}}{dp_T d\eta} = \sum_{abc}\int dx_a\, dx_b\, dz_c\, \Delta f_a(x_a, \mu_f)\, \Delta f_b(x_b, \mu_f)\, D_c^{\pi}(z_c, \mu'_f)$$
$$\times \frac{d\Delta\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^{\pi}/z_c, \mu_f, \mu'_f, \mu_r) + \mathcal{O}(\frac{\lambda}{p_T})^n$$

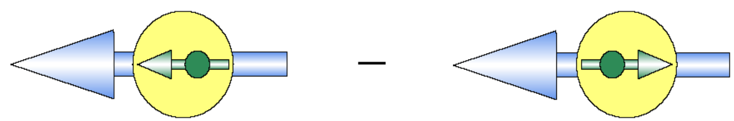
SPIN Dependant Parton Density Functions

In a proton with positive helicity we can find a parton:

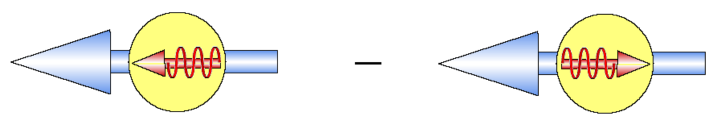
$g(x,Q^2)=$ 

$q(x,Q^2)=$ 

•We then Define **Δg , Δq , (Δf)** as the probability of finding a quark, gluon or antiquark with spin parallel or anti parallel to the spin of the nucleon.

$\Delta\ q(x,Q^2)$ 

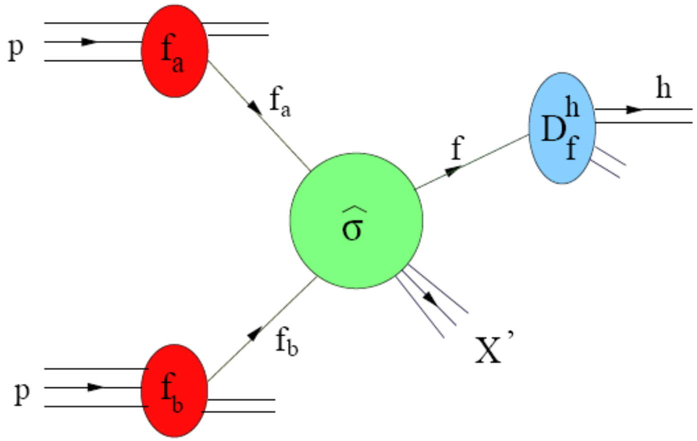
$=$

$\Delta\ g(x,Q^2)=$ 

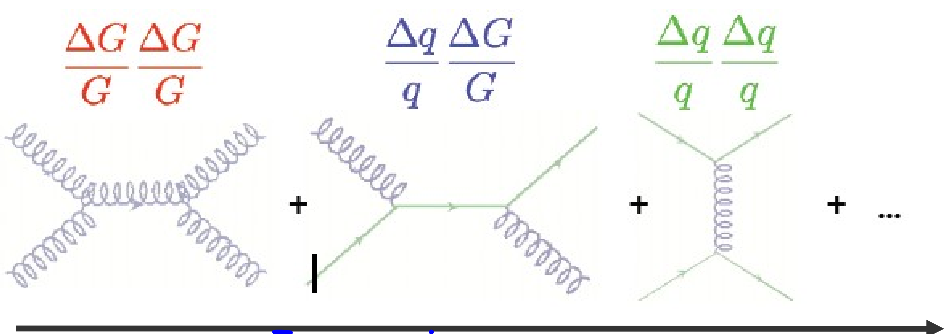
These integrals of Δ f multiplied by the spin of the parton f will give the amount of spin carried by each parton*.

*i.e for gluons :   **Amount of carried spin ~ Δ g*1**

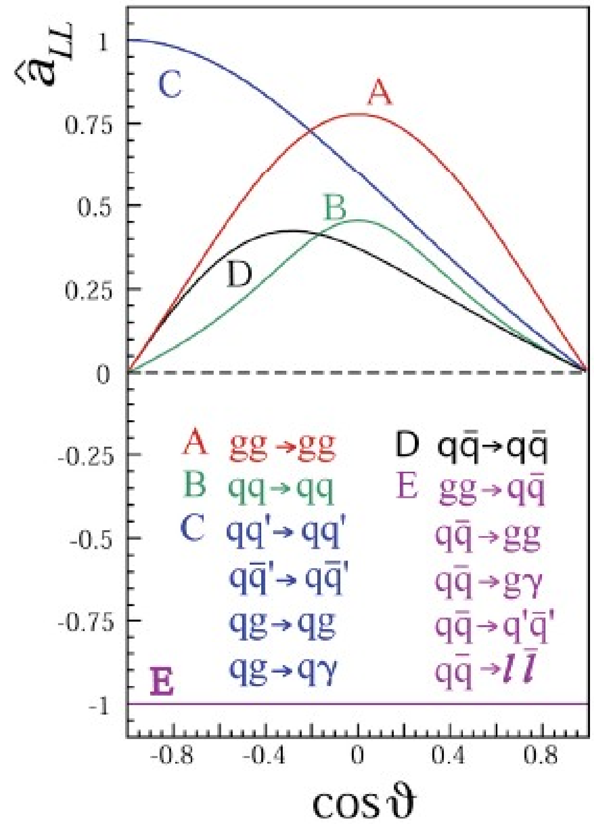
Accessing Δg with Asymmetries



$$A_{LL} = \frac{\sigma^{\square} - \sigma}{\sigma \;\; + \sigma} ? \frac{\Delta\sigma}{\sigma} = \hat{a}_{LL}(qg ? q\gamma) ? \frac{\Delta g(x_1)}{g(x_1)} ? \frac{\Delta q(x_2)}{q(x_2)}$$



Increasing x, p_T



Hard subprocess asymmetries (LO)

Asymmetries

- For Δ g the tools are measurements of helicity cross section asymmetries A_{LL}

$$A^{\pi}_{LL} = \Delta\sigma^{\pi}/\sigma^{\pi}$$

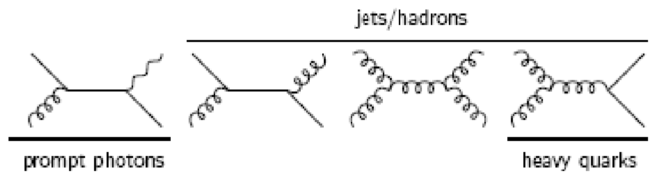
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_b P_y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

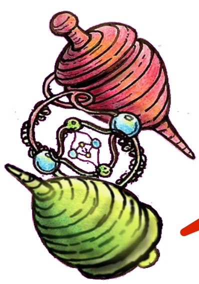
(N) Particle Yields
(R) Relative Luminosity
(P)Polarization

Direct Processes

Measuring double spin asymmetries in certain final states are the most valuable tool to measure polarized gluon (and quark) distribution functions in the proton.

The most accurate way to do so is the study of those processes which can be calculated in the framework of perturbative QCD.





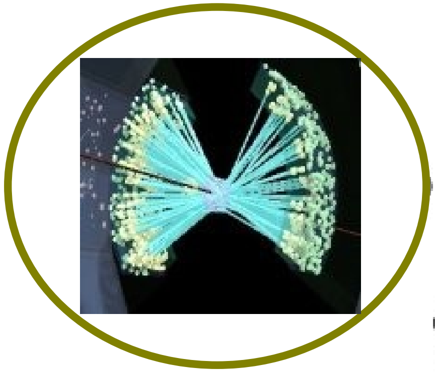
reaction	LO subprocesses	partons probed
$pp \to \text{jets}\, X$	$q\bar{q}, qq, qg, gg \to \text{jet}\, X$	Δq, Δg
$pp \to \pi X$	$q\bar{q}, qq, qg, gg \to \pi X$	Δq, Δg
$pp \to \gamma X$	$qg \to q\gamma$, $q\bar{q} \to g\gamma$	Δg
$pp \to Q\bar{Q}X$	$gg \to Q\bar{Q}$, $q\bar{q} \to Q\bar{Q}$	Δg

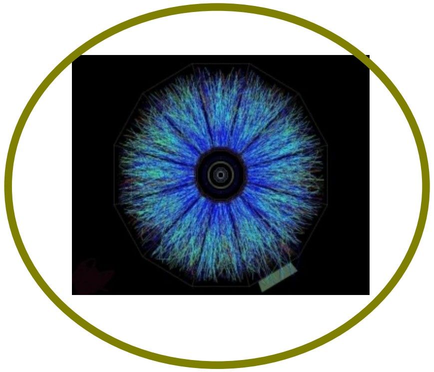
π MESON

- Zero spin and composed of first generation quarks
- Pseudo scalar under a parity transformation: pion currents couple to the axial vector current.
- Production of pions proceed from **gg** and **gq** initiated sub processes on proton-proton collisions

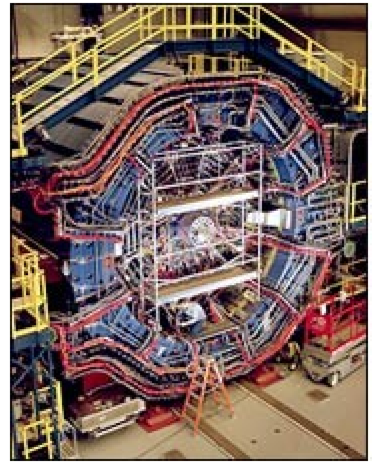
Shooting at Polarized Protons with Polarized Quarks

How's do we...?





RHIC's QCD Detectors



PHENIX Design philosophy:

Fine Granularity, Mass Resolution

High Data Rate

Good Particle ID

Limited Acceptance in central calorimetry and forward muon detectors

STAR :

Large acceptance with azimuthal symmetry

Good tracking, particle ID

Central & forward calorimetry

Today I will Focus on PHENIX Pion measurements

For STAR look: http://rnc.lbl.gov/~jhthomas/public/NimWeb/

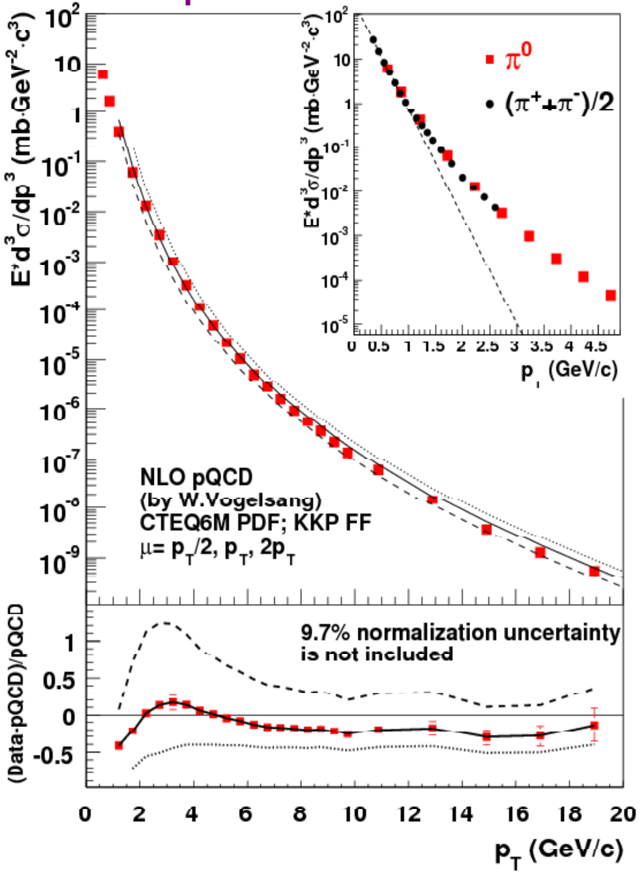
Both have collisions counters and zero-degree-calorimeters to characterize events

Are Perturbative Methods Valid at RHIC?

π^0 cross section measurement

PHENIX: π^0 mid-rapidity, 200GeV

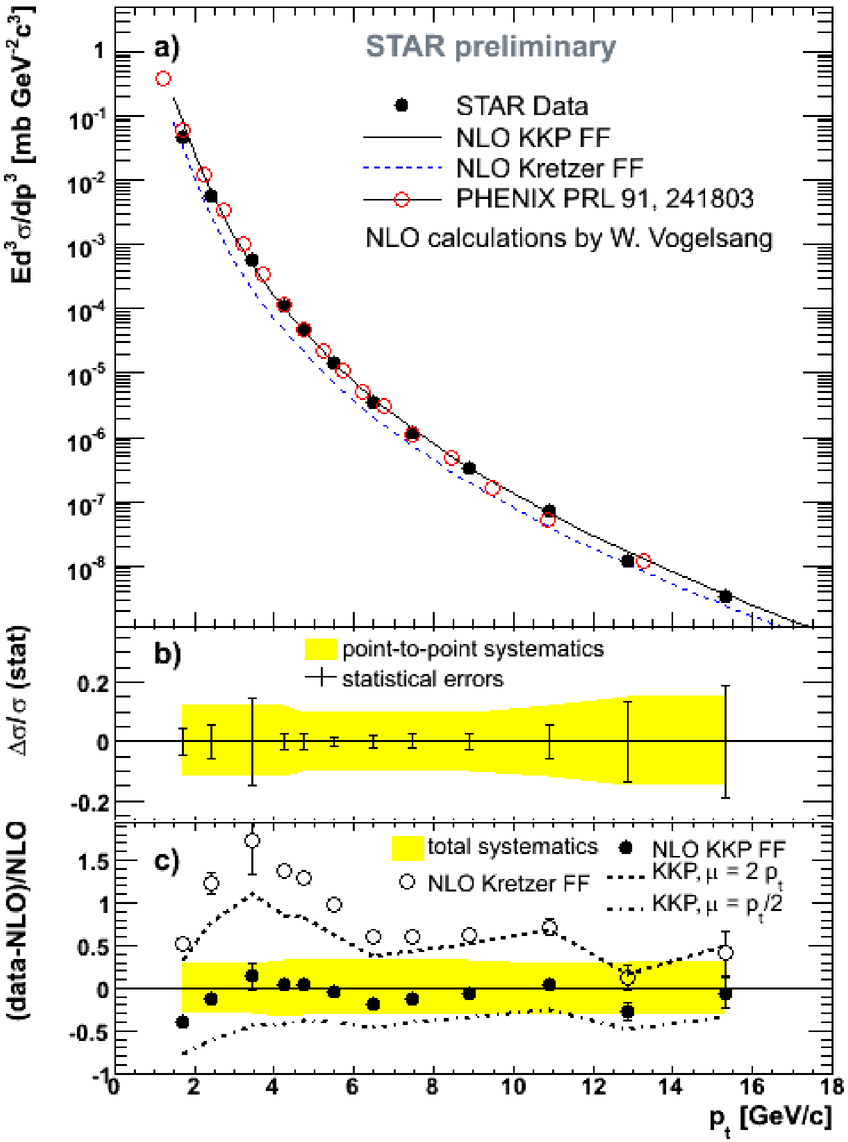
hep-ex-0704.3599



- Agreement between data and pQCD theory
- Shows that pQCD and unpolarized PDFs determined in DIS can describe pp data
- Choice of fragmentation function crucial (dominated by gluon fragmentation)
- Scale uncertainty still large at lower p_T<5 GeV

YES!

Are Perturbative Methods Valid at RHIC?



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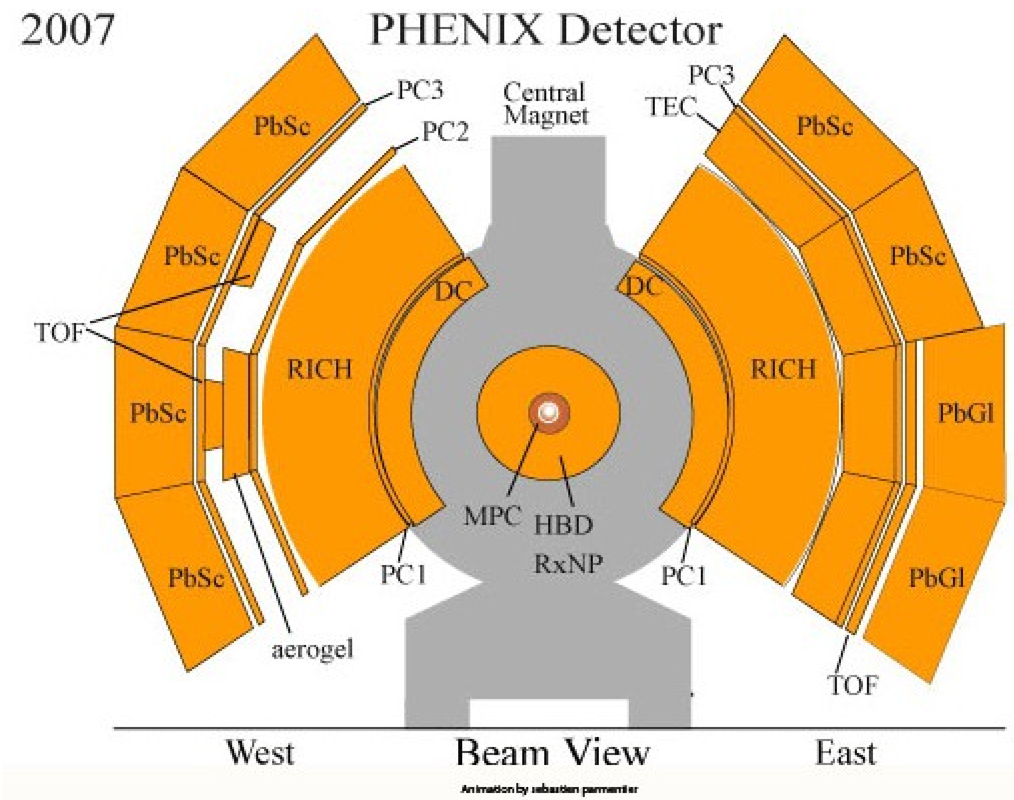
stent with previous results from PHENIX

YES!

PHENIX DETECTION of Pions

$\eta < |0.35|$, $\phi = 2 \times 90°$

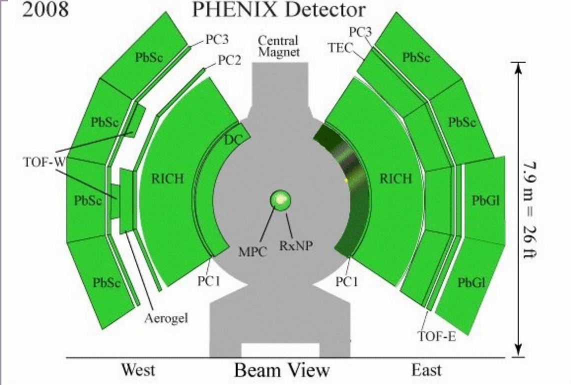


Central Detector:

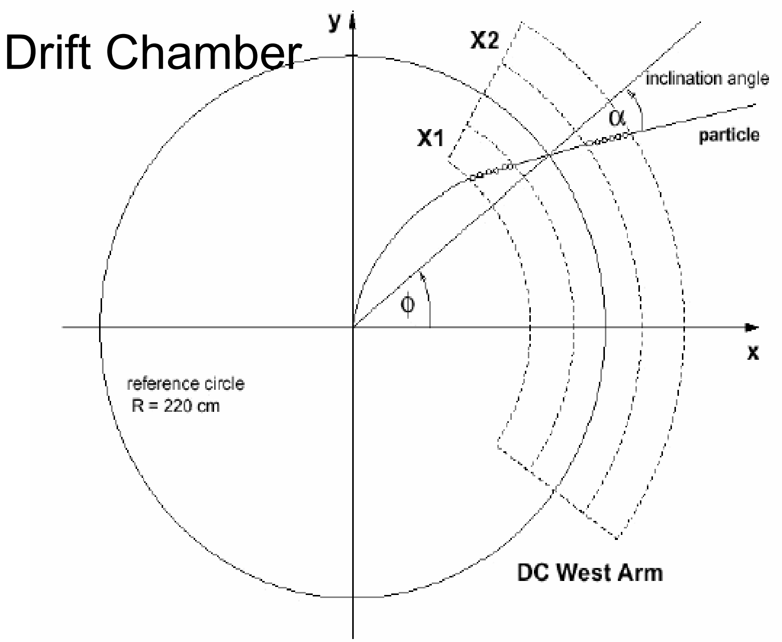
- π^0 detection
  - Electromagnetic Calorimeter
- High efficiency γ trigger
- π^+/π^-
  - Drift Chamber
  - Ring Imaging Cherenkov Detector
  - Pad Chambers

Global Detectors:

- Relative Luminosity
  - Beam-Beam Counter (BBC) $3.0 < \eta < 3.9$
  - Zero-Degree Calorimeter (ZDC)Acceptance: ±2 mrad
- Local Polarimetry - ZDC



Charged Tracks Detection



Drift Chamber:

- Precise measurement of charged particle's momentum
- Gives initial information for the global tracking in PHENIX

Acceptance

- 2 arms 90° in ϕ each
- ±90 cm in Z
- 0.7 units of η

Location:

- Radial :2.02<R<2.48 m
- Angular:
  - West: $-34^{\circ} < \phi < 56^{\circ}$
  - East : $125^{\circ} < \phi < 215^{\circ}$

– **To reconstruct charged particle track DC samples a few points in space along the path of the particle. One such point is called a "HIT"**

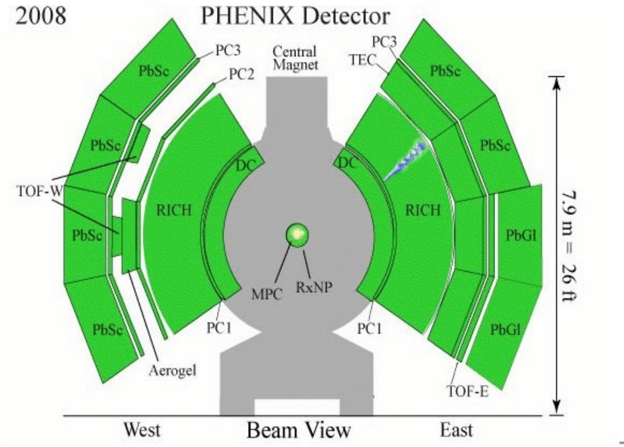
Detector

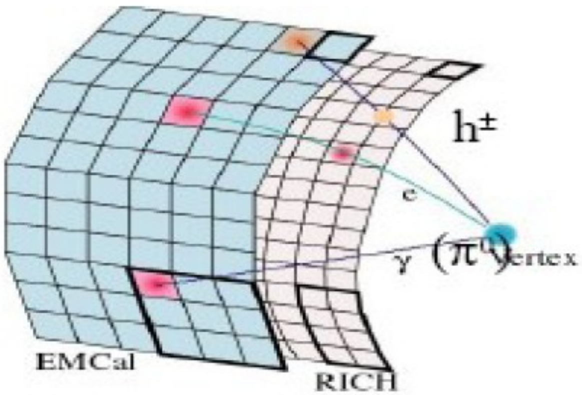
An Emcal-RICH coincidence trigger can be used to select tracks

Tracks can be divided into different categories according to RICH response, i.e.:

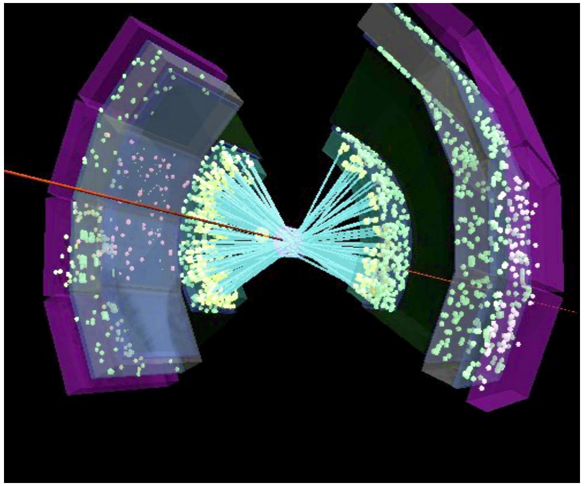
- RICH Hit: $e_{\pm}$ background and high-p_T $\pi_{\pm}$
- No RICH Hit: decay background and high-p_T K,p

Particle	Electron	Pion	Kaon	Proton
Threshold	30MeV/c	4.7GeV/c	16GeV/c	30GeV/c





Detector (EMCal)

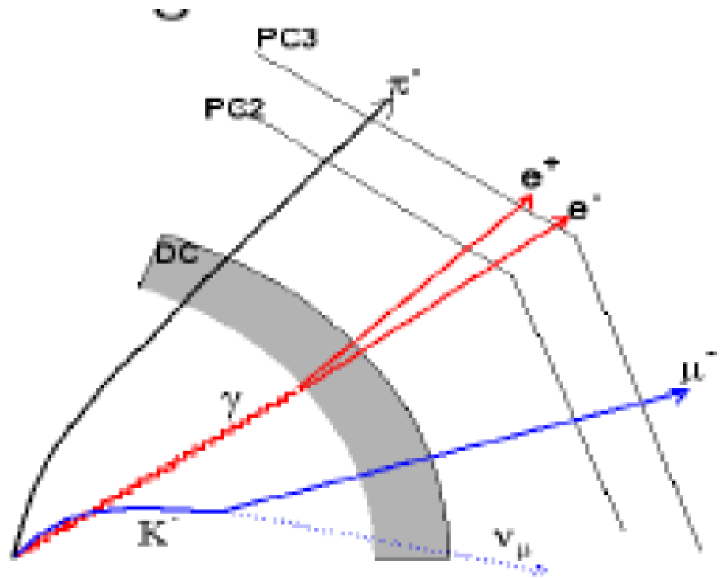


- Electrons and photons interact electromagnetically (bremsstrahlung and pair production) and produce electromagnetic showers.
- Hadrons in this energy range are typically Minimum Ionizing Particles (MIPs) and deposit only part of their energy in hadronic showers(only 1 interaction length -1/e~0.4)
- The calorimeter measures **position**, **energy** and **time of flight** of the incoming particles

Pad Chambers Projections

•Projections of reconstructed DC tracks to the pad chambers or the EMCal.

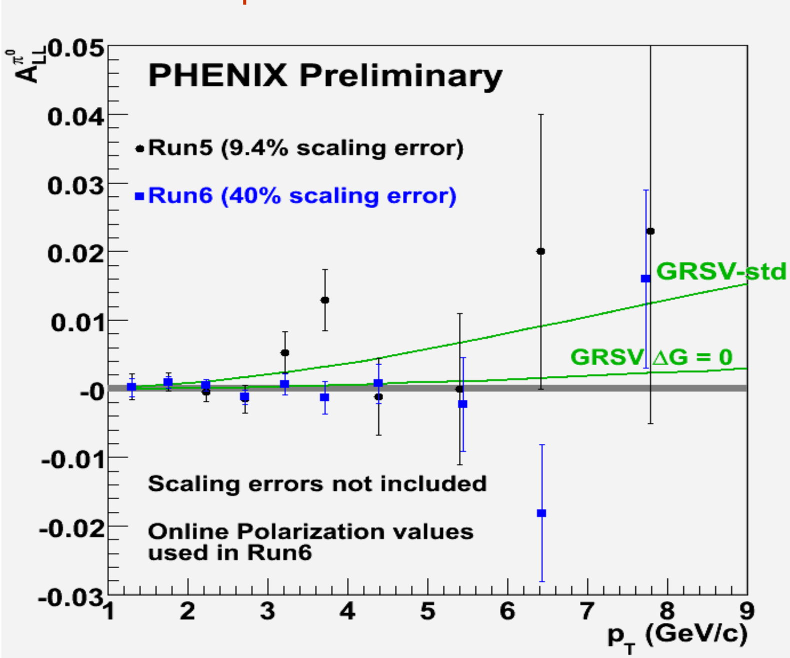
•These projections can be used to reduce the background from secondary particles (particles not originating from the event vertex) by applying cuts on the deviation of the position of the actual associated hits from the track model projection.



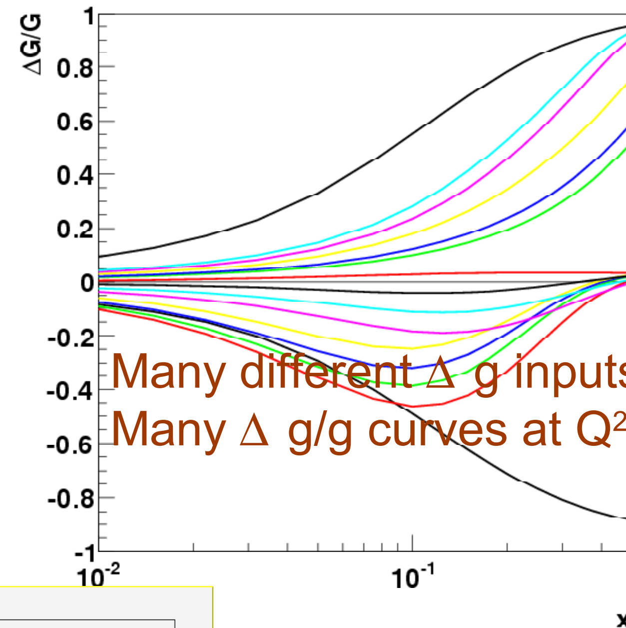
π^0 Asymmetries

Measured asymmetries for
$pp \to \pi^0 X$ from Run 5 ,Run 6

Run3,4,5: PRL 93, 202002; PRD 73, 091102;
hep-ex-0704.3599

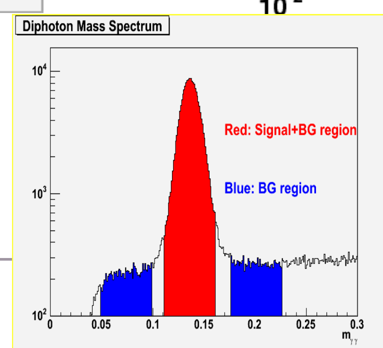


GRSV model (NLO)



Many different Δ g inputs $\Rightarrow$
Many Δ g/g curves at Q^2=1

- Asymmetry of combinatorial background estimated from sidebands and subtracted



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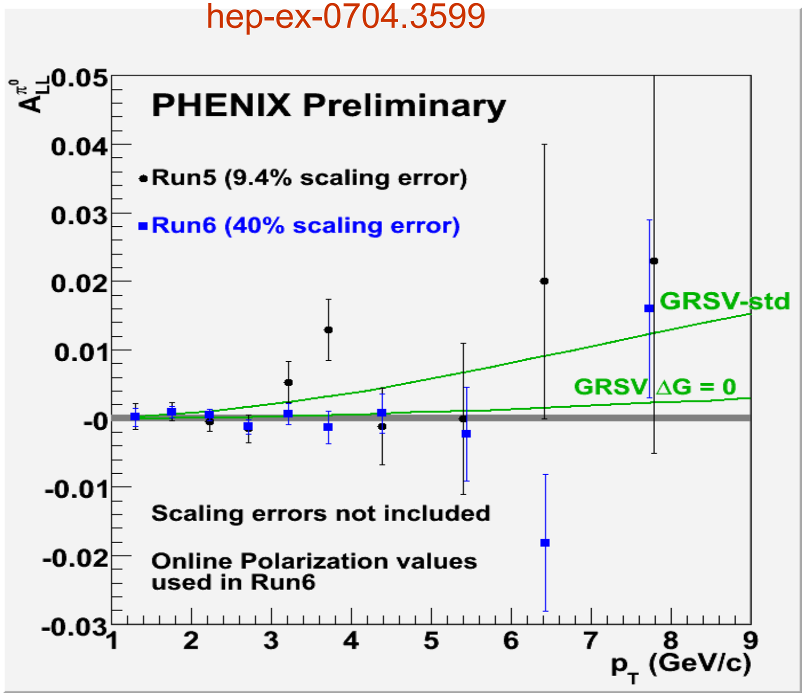

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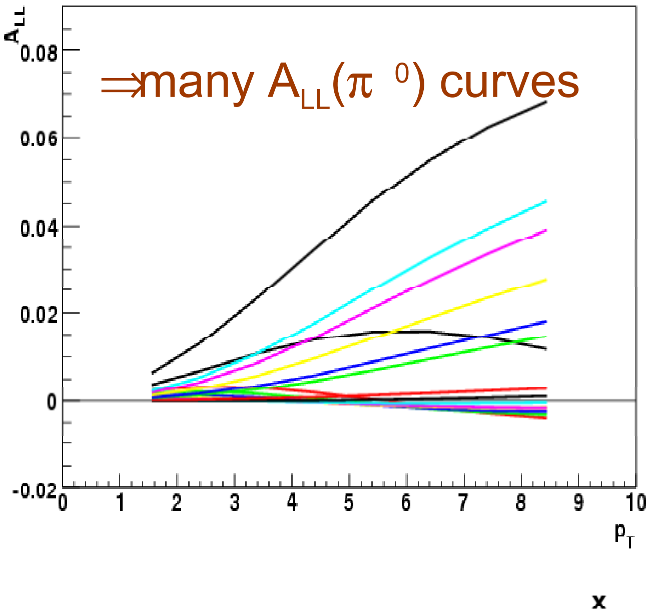
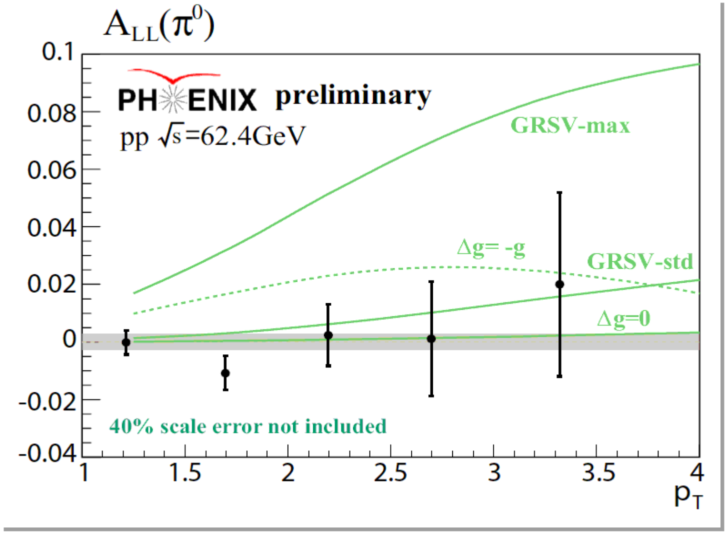
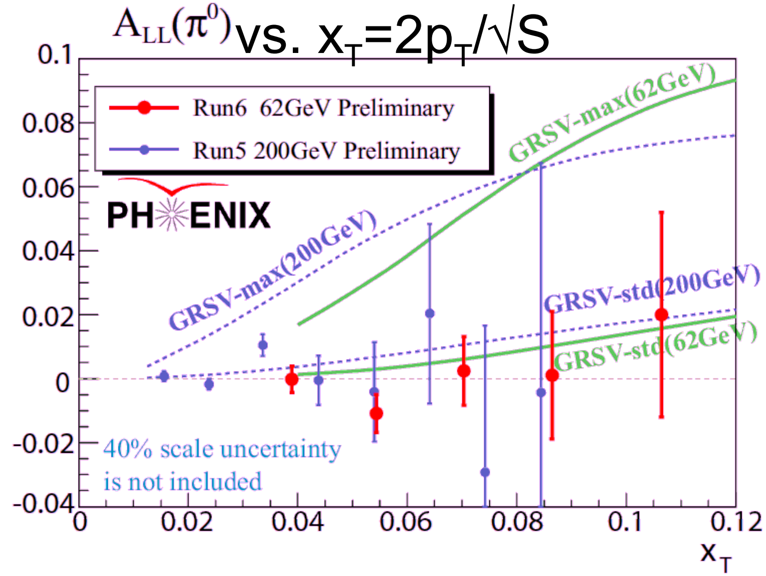


- Asymmetry of combinatorial background estimated from sidebands and subtracted

Information from π^0 Asymmetries?

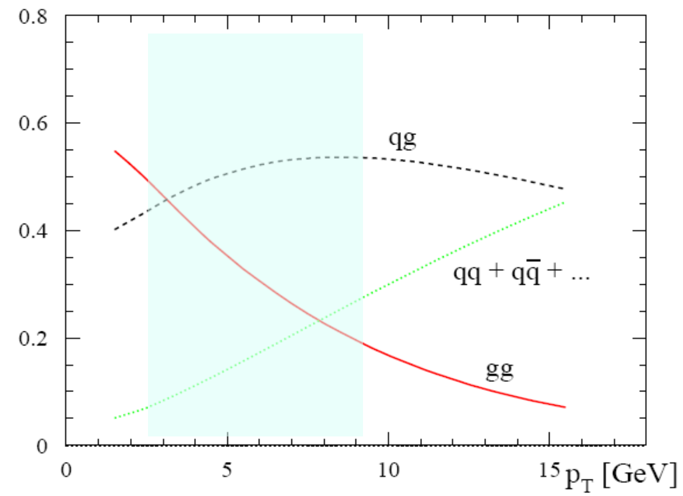
- Inclusive π^0 A_{LL} cannot access $\Delta g(x)$ directly
  - Only sensitive to an average over a wide x range
  - No conclusions about moment of $\Delta g(x)$ possible without a model for its shape
- More (indirect) information from varying cms energies
  - Higher (500 GeV) $\rightarrow$ lower x
  - Smaller (62 GeV) $\rightarrow$ higher x (and larger scale uncertainty)





What can Inclusive Pion $A_{LL}(pp\to\pi X)$ tells us

Initial state parton configurations contributing to unpolarized cross section (Fractions)



W. Vogelsang et al.

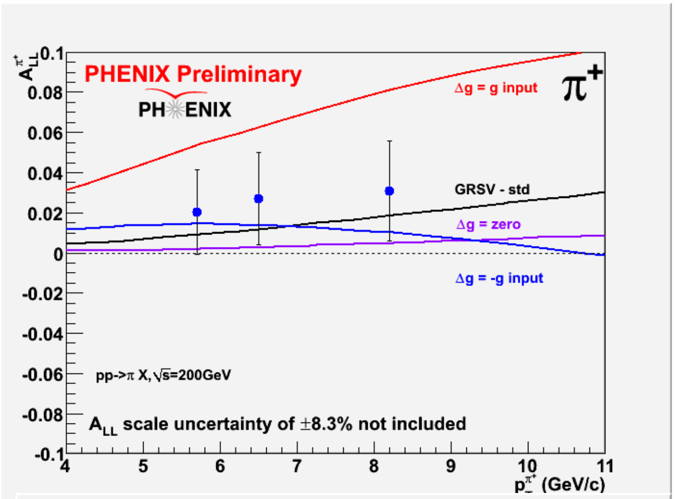
- Dominated by gg for p_T<3, qg for 3<p_T<10 GeV

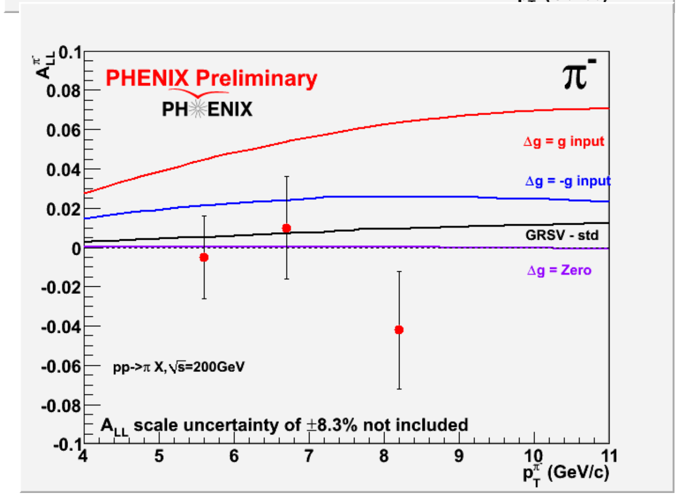
-The pions's fragmentation function contains all long distance interactions, they are not calculable, but they are universal

- We can compare $A_{LL}\pi^{\pm}$ vs $A_{LL}\pi^0$

qg starts to dominate for $p_T >\sim 5$GeV and $D_u^{\pi^+} > D_u^{\pi^0} > D_u^{\pi^-}$
Expect sensitivity to sign of ΔG, e.g., positive $A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$

$\pi^{+,-}$ Asymmetries





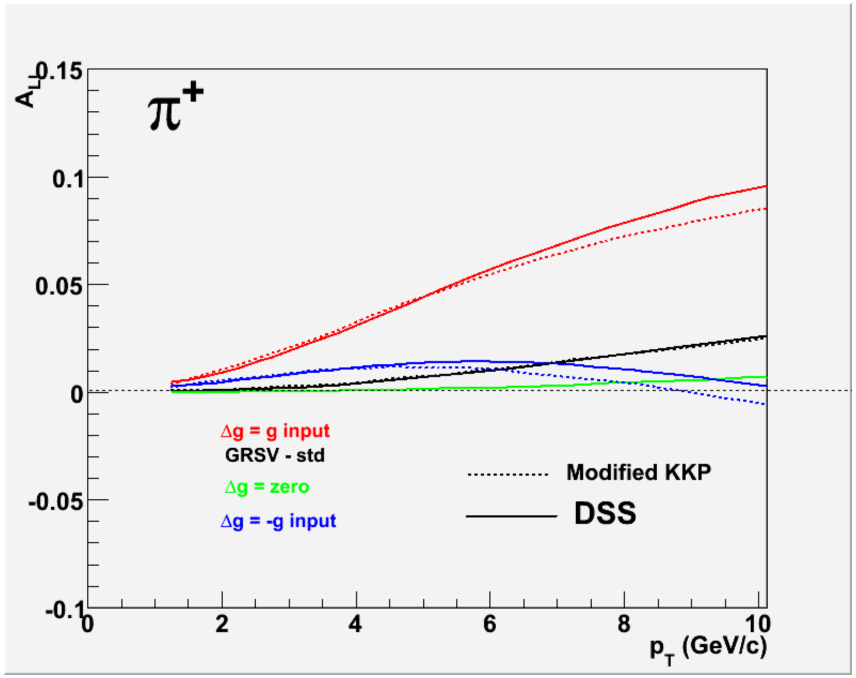
Charged pions above 4.7 GeV identified with RICH.

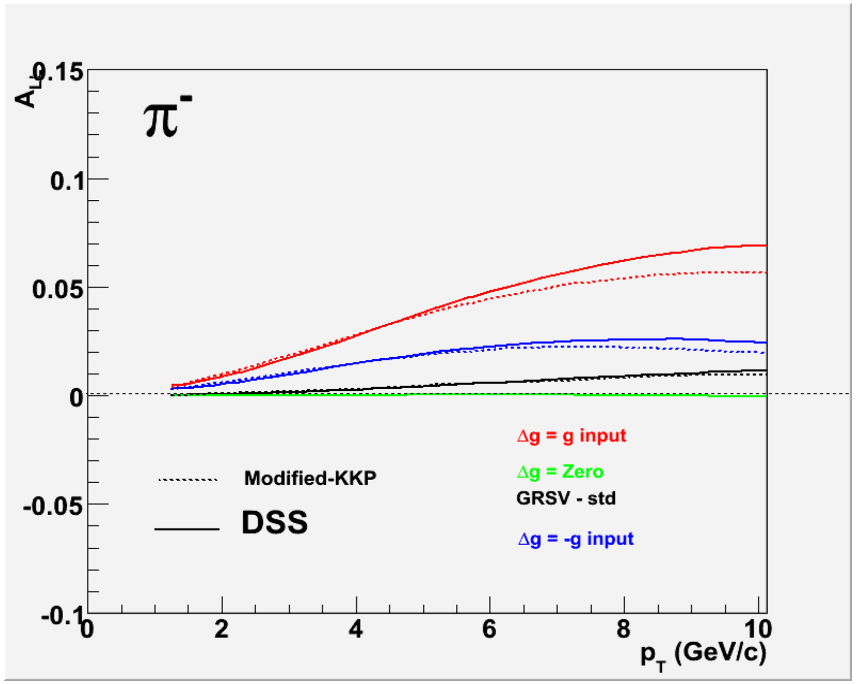
At higher p_T, qg interactions become dominant: $\Delta q \Delta g$ term.

A_{LL} becomes significant allowing access to the sign of ΔG

❖ **New set from M. Stratmann et al. is the first to use charged separated π data from SIDIS for fragmentation functions**

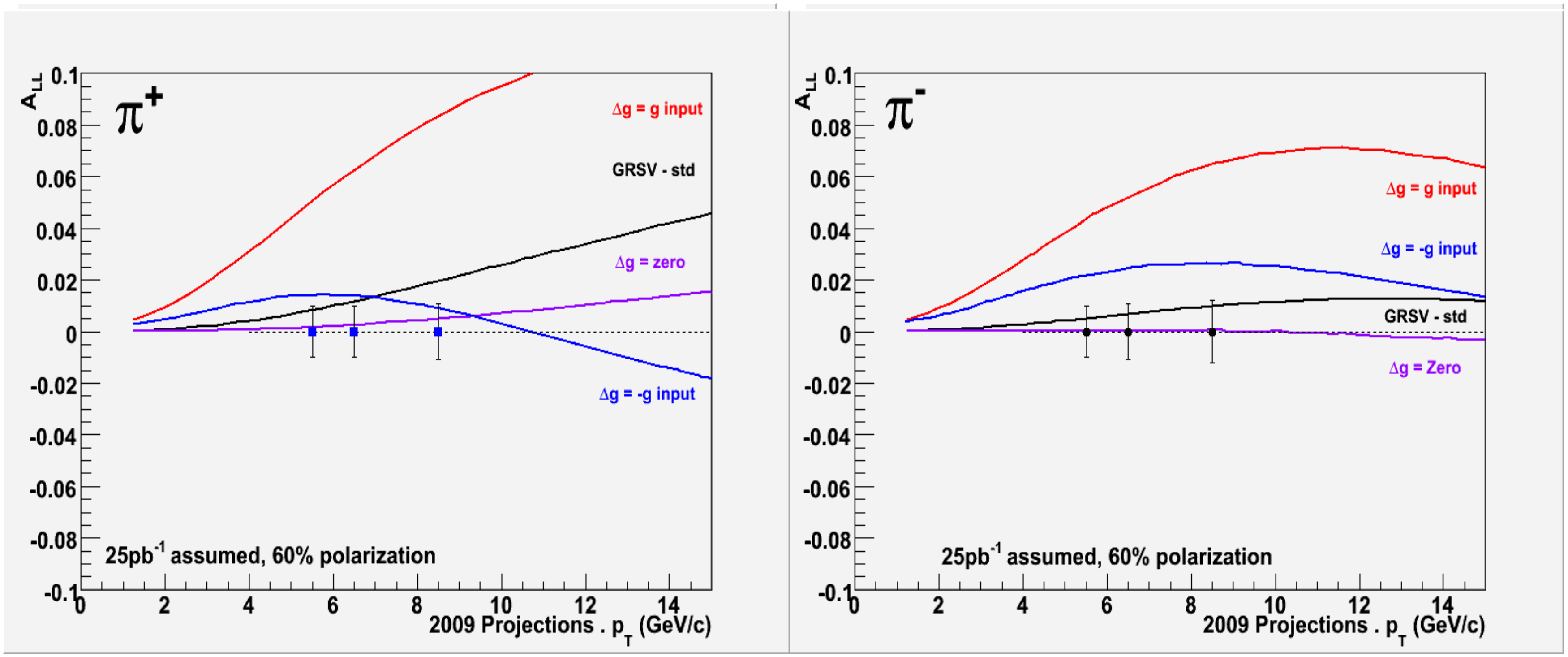
Information from $\pi^{+,-}$ Asymmetries





- Different sensitivities of charged pions to Δu and Δd provide more sensitivity to sign of Δg via qg scattering
- "Model independent" conclusion possible once enough data is available.

Information from $\pi^{+,-}$ Asymmetries



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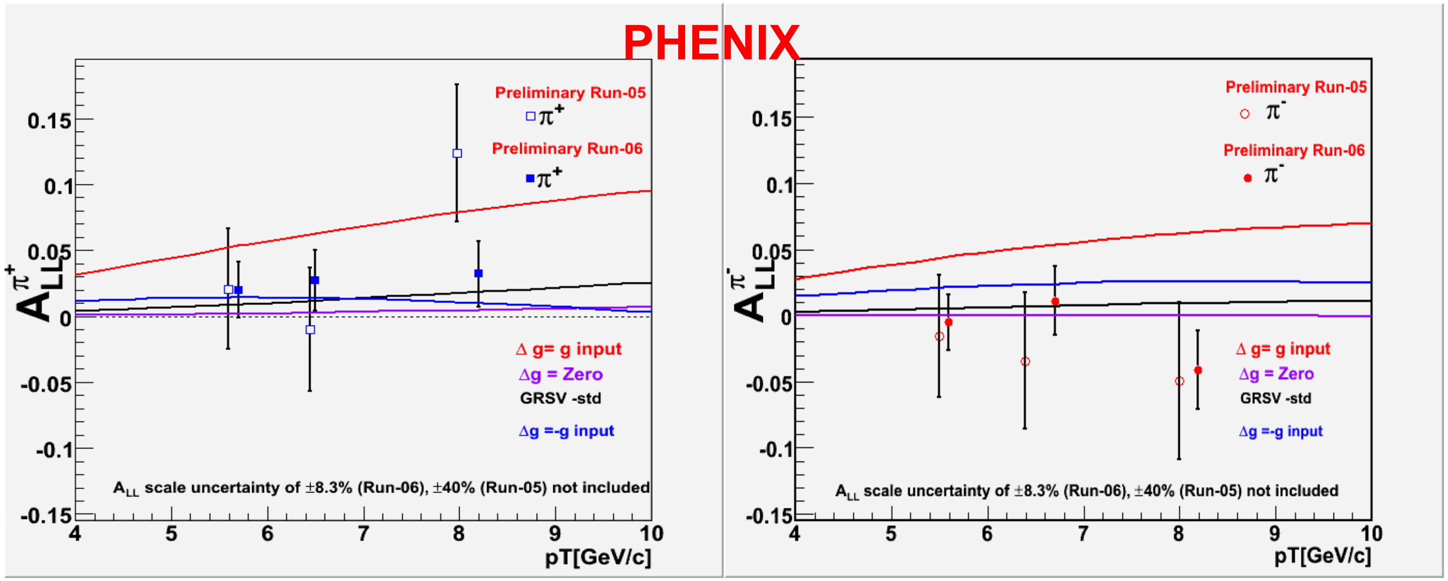
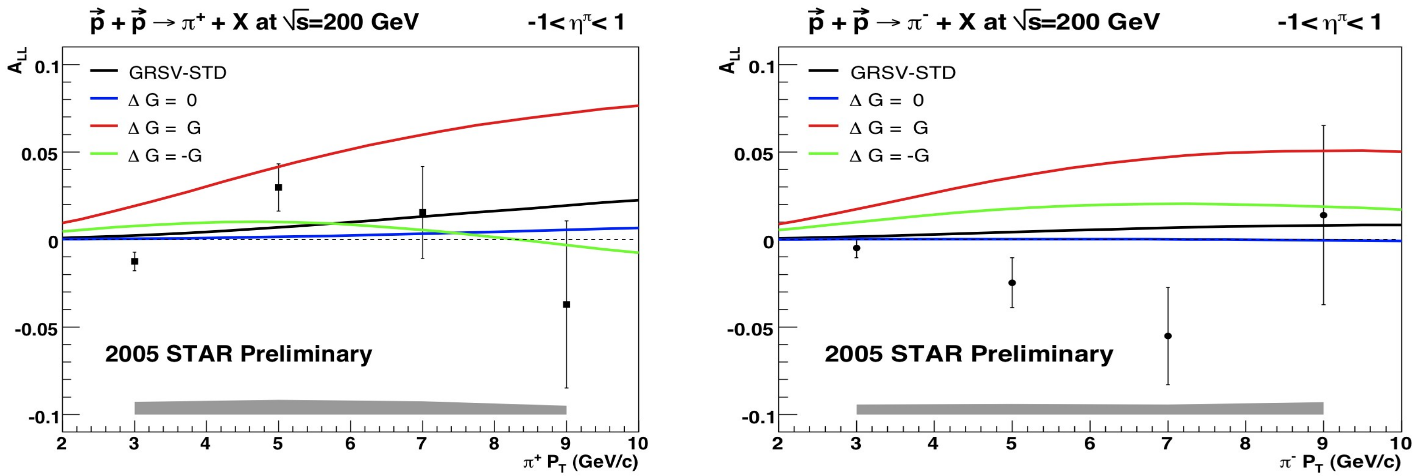
$\pi^{+,-}$ Asymmetries

PHENIX





STAR

(Adam Kocolosky's Work see arXiv:hep-ex/0612005v1)

$\Delta G(x)$ Global Analysis

- Results from various channels combined into single results for $\Delta G(x)$
- Correlations with other PDFs for each channel properly accounted
- Every single channel result is usually smeared over x $\Rightarrow$ global analysis can do deconvolution (map of ΔG vs x) based on various channel results
- NLO pQCD framework can be used
- Global analysis framework already exist for pol. DIS data and being developed to include RHIC pp data, by different groups

One of the attempts of global analysis by AAC Collaboration using PHENIX π^0 -Preliminary data

Now Run5-Final and Run6-Preliminary π^0 data are available!!!

ΔG(x) Global Analysis Latest Results

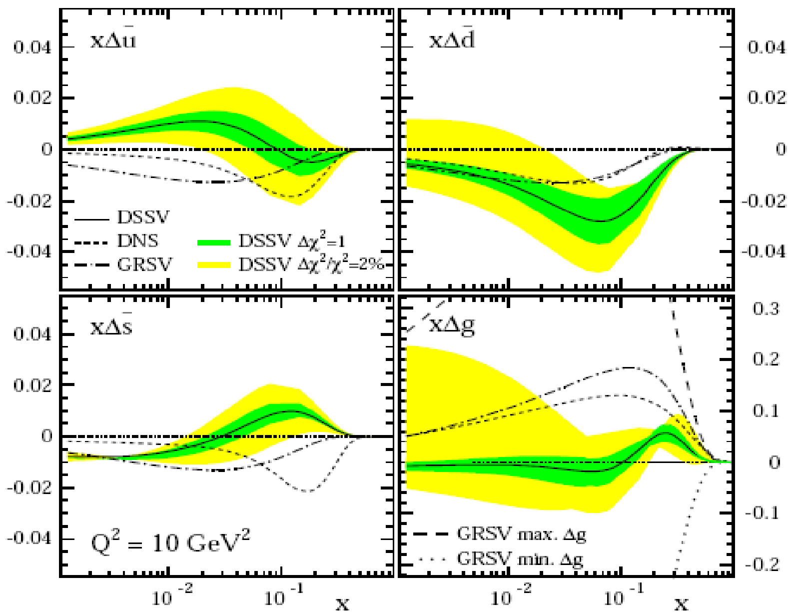


FIG. 2: Our polarized sea and gluon densities compared to previous fits [6, 8]. The shaded bands correspond to alternative fits with $\Delta\chi^2 = 1$ and $\Delta\chi^2/\chi^2 = 2\%$ (see text).

-Flavor dependence of the sea

-SU3 symmetry breaking?.

"We also find that the SIDIS data give rise to a Robust pattern for the sea polarizations, clearly deviating from SU(3) symmetry, **which awaits further clarification from the upcoming W boson Program at RHIC"**

Global Analysis of Helicity Parton Densities and Their Uncertainties

(de Florian, Sassot, Stratmann and Wogelsang) ArXiv:0804.0422 (April 2008)

ΔG(x) Global Analysis Latest Results

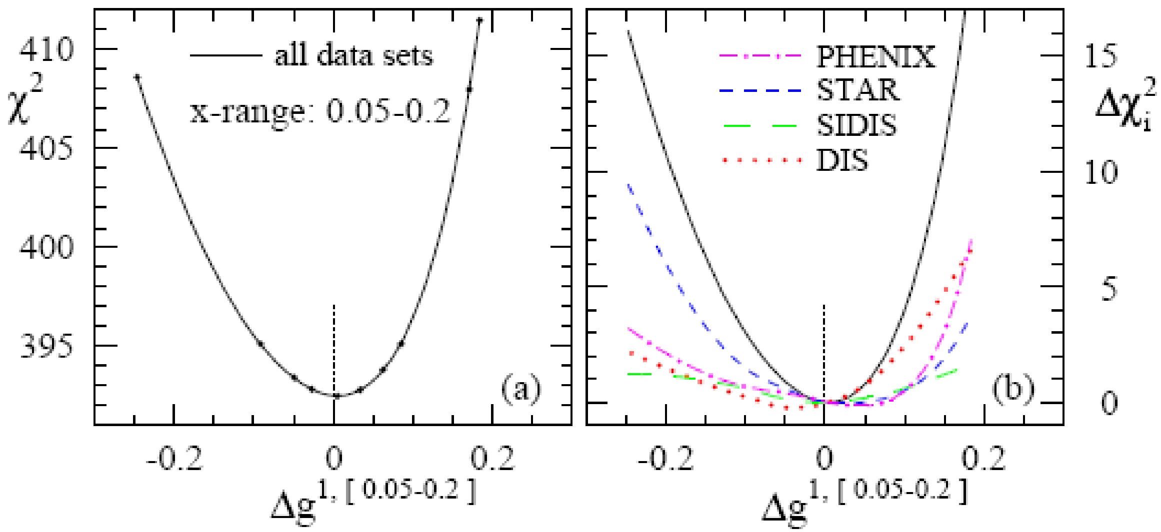


FIG. 3: The χ^2 profile (a) and partial contributions $\Delta\chi_i^2$ (b) of the data sets for variations of $\Delta g^{1,[0.05-0.2]}$ at $Q^2 = 10\,\text{GeV}^2$.

ArXiv:0804.0422 (April 2008)

-A first demonstration that p-p data can be included in a consistent way in a NLO pQCD calculation.

-RHIC data set significantly constraints on the gluon helicity distribution

-"Inclusion of theoretical uncertainties and the treatment of experimental ones should and will be improved"

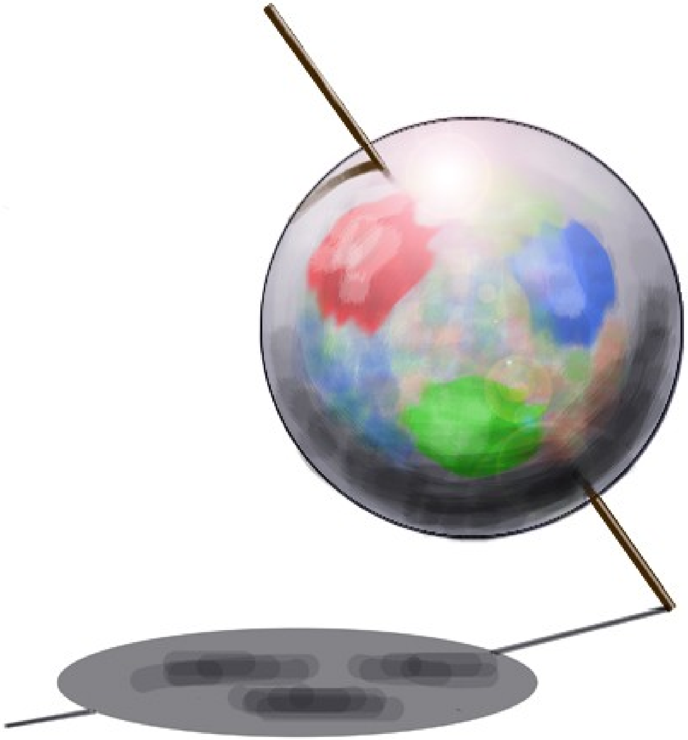
Conclusion

- Charged pion data are getting ready to be included in (the next round of) global QCD fits, thanks to new/improved Ffs

- Neutral Pions: While there may be an indication of a small contribution , *we need more* probes to disentangle all the contributions to the proton spin.

Comparison of all three pion species can give some definate information about both the sign and magnitude of Delta G.

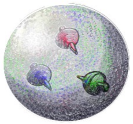
Thank You



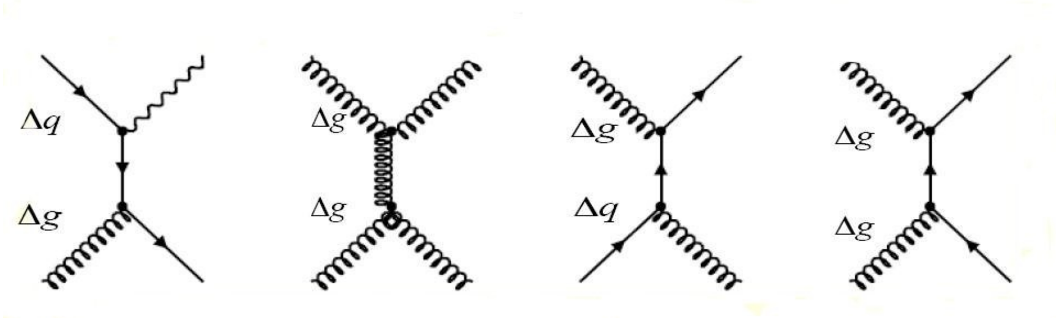
EXTRA SLIDES

QCD SPIN PICTURE

QCD is non-abelian gauge theory that describes the interaction of massless spin ½ objects that possess an internal degree of freedom called **color**.

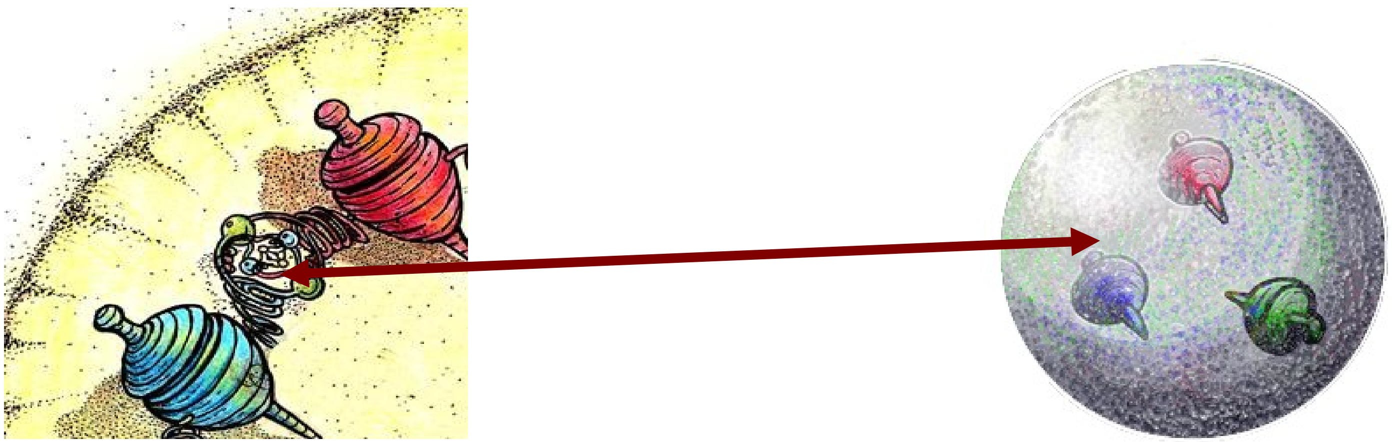


The primary goal of **QCD** spin is to describe hadrons in terms of **quarks** and **gluons**



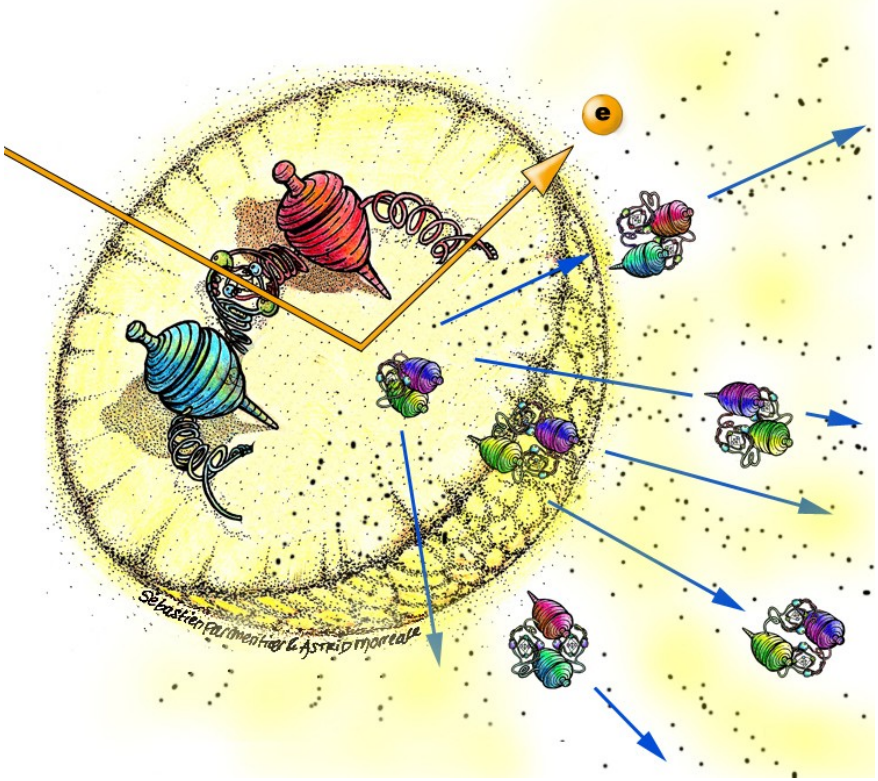
QCD PICTURE

For interactions between quarks at very short distances (large momentum transfers) the theory looks more like a free-field theory, without interactions



This is the justification for the parton model (QPM) and the use of perturbative methods for large momentum reactions.

Breaking the Spring



Assume struck quark inside the proton carries momentum ξ P and look for ξ

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\sum_q \int_0^1 d\xi q(\xi) e_q^2 \frac{x}{2}\left[1+(1-y)^2\right]\delta(x-\xi), \quad F_2 = 2xF_1 = \sum_q e_q^2 x q(x).$$

The *Ellis-Jaffe* Sum Rule

Ellis and Jaffe derived an expression in 1974 for the first moment of the polarized structure function from that of the neutron. Γ_1^p **and** Γ_1^n
Requiring exact $SU_f(3)$ flavor symmetry, they derived

$\Delta u - \Delta d = F + D$
$\Delta u + \Delta d - 2\Delta s = 3F - D$

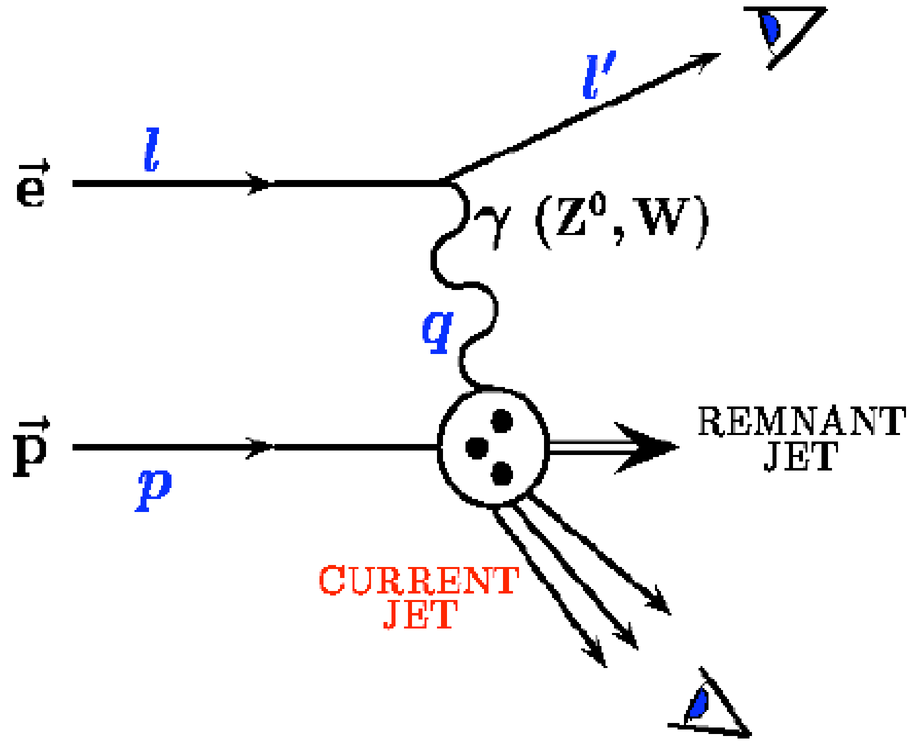
hyperon decays provided the data for F and D ($SU_f(3)$ coupling constants)
assuming that the quark sea Δs does not contribute (=0)
then the up and down contributions are:
$\Delta u = 2F = 0.93$ and $\Delta d = F - D = -0.33$

Under these assumptions, The Ellis-Jaffe Sum Rule gives us:

$\Gamma_1^p = 0.19$ and $\Sigma = 0.60$

DIS Variables

The energy transfer or hardness: $Q^2 = -q^2 = -(p_l - p_{l'})^2 \approx 2\, E_l\, E_{l'}(1 - \cos\theta)$,



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p\cdot q}$$

$$y = \frac{p\cdot q}{p\cdot l}$$

$$s = 4E_eE_p$$

$$W = (q+p)^2$$

Relative Luminosity

Use BBCs at ± 1.5 m from the interaction point to measure bunch-by-bunch luminosity

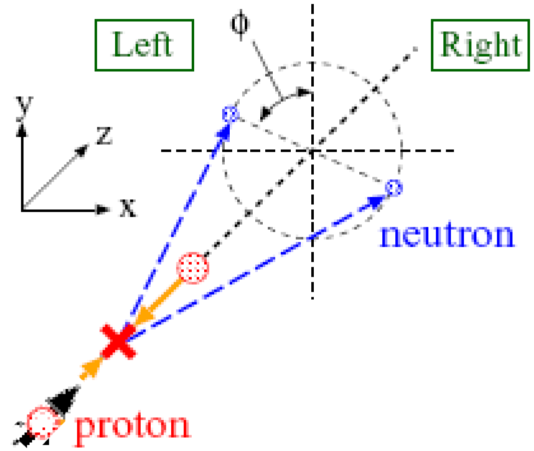
$L_i = N_i/(\sigma \bullet \text{Efficiency})$, $\sigma \bullet \text{Eff.} = \text{const.} = 22.9\text{mb} \pm 9.7\%$

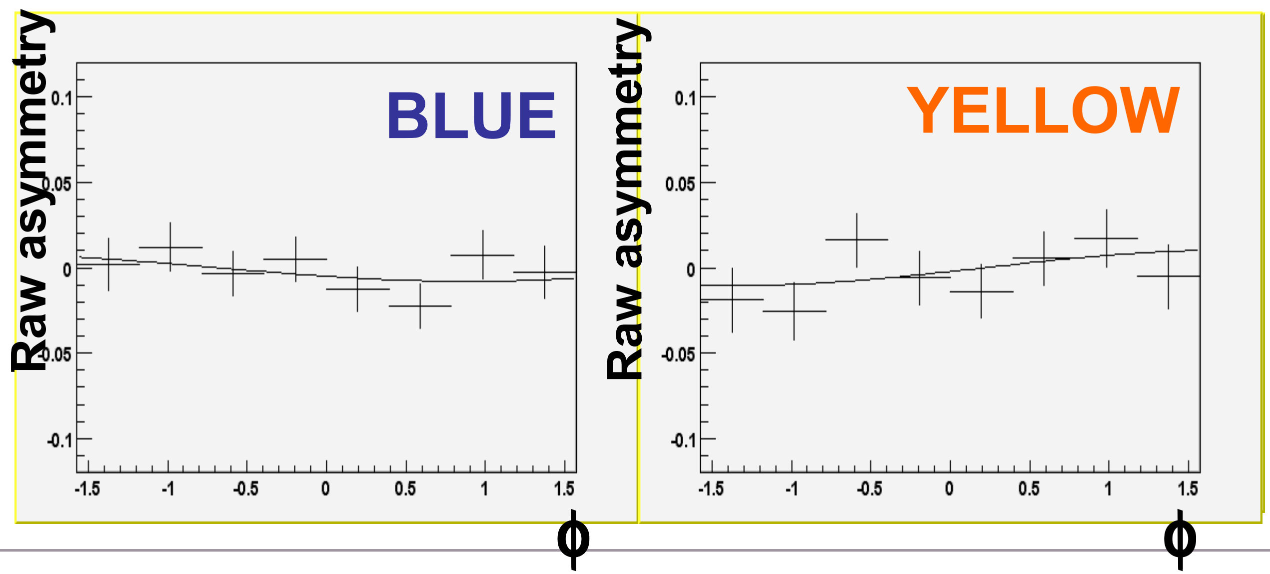
- Use independent measurement from ZDCs (± 18m) to check for intrinsic luminosity asymmetry

$$\frac{N^{BBC}}{N^{ZDC}} \approx c\left(1 + P_B P_Y (A_{LL}^{BBC} - A_{LL}^{ZDC})\right)$$

Local Polarimetry at PHENIX

- Use Zero Degree Calorimeter (ZDC) to measure a L-R and U-D asymmetry in forward neutrons (Acceptance: ±2 mrad).
- When transversely polarized, we see clear asymmetry.
- When longitudinally polarized, there should be no asymmetry.





Idea: Use neutron asymmetry to study transversely polarized component.

From Kieran Boyle'